PROCEEDINGS *of the* FIFTH BERKELEY SYMPOSIUM ON MATHEMATICAL STATISTICS AND PROBABILITY

Held at the Statistical Laboratory
University of California
June 21–July 18, 1965
and
December 27, 1965–January 7, 1966

with the support of
University of California
National Science Foundation
National Institutes of Health
Air Force Office of Scientific Research
Army Research Office
Office of Naval Research

VOLUME V

WEATHER MODIFICATION

EDITED BY LUCIEN M. LE CAM
AND JERZY NEYMAN

UNIVERSITY OF CALIFORNIA PRESS
BERKELEY AND LOS ANGELES
1967

CLOUD SEEDING EXPERIMENTS IN AUSTRALIA

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1. Introduction

Cloud seeding experiments in Australia were commenced in 1947 by the Radiophysics Division of the Commonwealth Scientific and Industrial Research Organization, immediately following the pioneering work of Schaefer. Early tests using dry ice showed (Smith [5], Squires and Smith [13]) that cloud conditions favorable for seeding were relatively common but that the method, though effective, was comparatively costly and therefore of limited use for large areas.

Preliminary experiments in which silver iodide smoke was released from the ground yielded no results that could be detected. Measurements [10], [11] showed that the ice nucleating properties of the silver iodide smoke were rapidly reduced on exposure to daylight. Further, in Australian conditions where (except in winter on isolated mountains) the freezing level is always at least several thousand feet above the ground, the smoke rose only slowly to cloud height. Thus, if the smoke was to be introduced into clouds at levels where it might be effective, it was necessary to release it from aircraft and appropriate equipment was developed and tested (Smith *et al.* [12]).

This paper describes cloud seeding experiments using this method of seeding, leading to suggestions for improvement in the experimental design.

2. Experiments on single clouds

Preliminary experiments (Warner and Twomey [14]) were first performed in which silver iodide smoke was released from an aircraft into single supercooled clouds with the intention of stimulating rain. The results were encouraging, and a fully randomized series of trials was undertaken (Bethwaite *et al.* [2]). Experiments were performed only as cumulus clouds complied to a fixed specification; they had to be supercooled, reasonably isolated, deep, of long duration and without excessive shear, and not within 30 km of any other cloud which was raining or glaciated. The cloud was then either seeded or not seeded according to a random sequence. The subsequent history of the cloud was observed, and any rain which fell from it was measured by means of an impactor mounted on an aircraft, the crew of which did not know whether the cloud had been seeded or not.

The total rainfall from each cloud is displayed in figure 1, seeded and unseeded cases being separated. The display is confined to clouds whose tops were $-10°$ C or colder and where no appreciable rain developed from nearby clouds within 30 minutes of seeding. More rain fell from the seeded than from the unseeded clouds, the one sided significance level was about 0.02 and the conclusion was drawn that the seeding increased the rainfall.

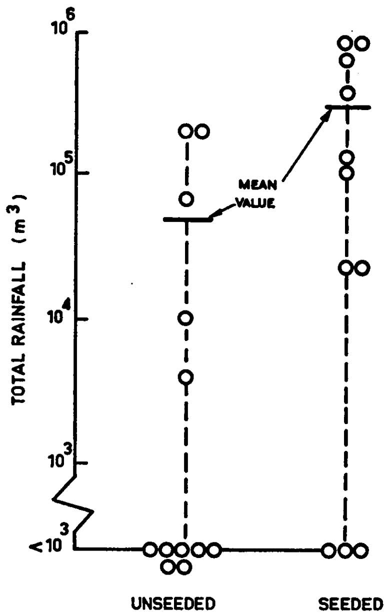

FIGURE 1

Total rainfall from isolated cumulus clouds.
Tops $-10°$ C or colder.
Seeded and unseeded.

In these experiments the mean rainfall from seeded clouds exceeded that from unseeded clouds by 2×10^5 m^3; if this result could be achieved 500 times per year in an area of 1000 km^2, it would represent an increase of 10 cm in the annual rainfall. In suitable climatic regions this result appears to be possible, and suggests the desirability of experiments to find out if this type of cloud seeding can increase the rainfall over an area.

3. Area experiments

3.1. *Description.* Cloud seeding experiments of two broadly similar types have been performed in Australia; one of the first type took place in the Snowy Mountains [9] and three of the second type in South Australia, New England

and the Warragamba Catchment [6], [7], [8]. Full details and the raw data for these experiments are contained in annual reports issued by the Radiophysics Division of the CSIRO, Sydney, Australia. Each experiment used two areas of 2000 to 7000 km^2, the rainfall in each being measured by a network of 30 to 150 gages. The areas are shown in figure 2. Time during the experiment was

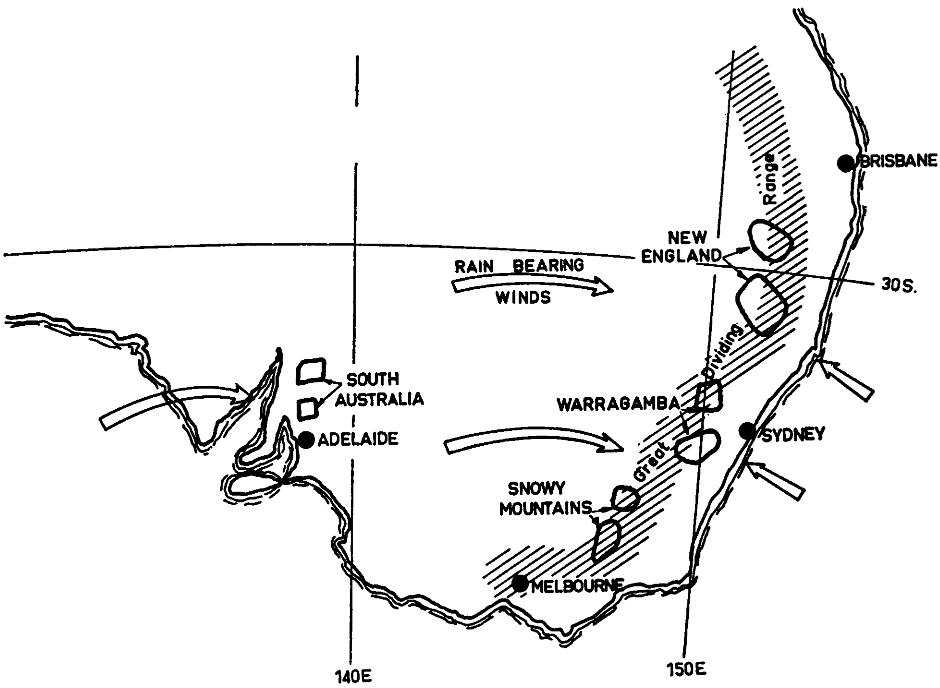

FIGURE 2

Location of cloud seeding experiments in South Eastern Australia.

divided into "periods" of about 14 days' duration, but changing on forecast fine days. An exception was the Warragamba experiment where the period length was one day.

In the Snowy Mountains experiment the two areas were used as target and control respectively, and during any one period a random process determined whether clouds over the target area should or should not be seeded. In the other experiments, clouds over one or the other area were seeded, a random process determining which of the two was used as the target during any period.

In other respects the experiments were similar. The purpose was to establish whether the rainfall over a specified area could be increased. The operational objective was to seed as many as possible of the deep, supercooled clouds passing over the area, cumulus being seeded at the base and stratiform clouds at the $-5°$ C to $-10°$ C level.

The duration of the experiments was three to six years. They operated continuously except that there was provision for suspending them in periods of excessive rainfall (the decision being taken by a "referee" who did not know the seeding sequence), and some of them were shut down in specified seasons, *e.g.* in South Australia in summer when there are very few clouds, and in New England during the wheat harvest when rain is not desired.

The topography of South East Australia is dominated by the Great Dividing Range. This, with the prevailing rain bearing winds are shown in figure 2. The Snowy Mountains and New England experiments were similar in that both were on the western slopes of the Range and were affected mainly by continental or semi-continental airstreams. The South Australian experiment was near the coast in predominantly maritime air, and the Warragamba experiment, situated towards the eastern side of the range, received some maritime and some continental type weather.

Other experiments of similar type have been performed. One was commenced in Australia, in the Darling Downs of Queensland, but was suspended after two years' rather unsuccessful operation in a subtropical climate substantially different from that of the others; other experiments have been performed overseas. These are not considered.

3.2. *Area experiments—preliminary results.* It was expected before the experiments started that some would give evidence of rainfall increases due to

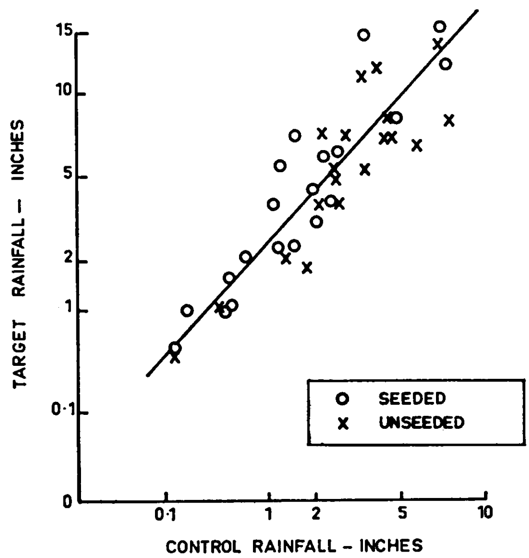

FIGURE 3

Snowy Mountains experiment.
First two years' results.
Period rainfalls in target and control areas.

seeding while others might not, depending on whether the climate of the area concerned provided plenty of clouds suitable for seeding or not. The more continental type climates (that is, Snowy Mountains and New England) were thought likely to be the most favorable, as a higher proportion of rain should form by the ice crystal process than in more maritime climates.

Preliminary results appeared to support these expectations. In South Australia and Warragamba, with maritime or partly maritime climates, the first year's results gave no indication that seeding had any detectable effect. However, initial results in the Snowy Mountains and New England were extremely promising.

Figure 3 shows a plot of the period rainfalls in the Snowy Mountains target and control areas, for the first two years' operation, with seeded and unseeded periods distinguished. The Double Ratio T/C (seeded)/T/C (unseeded), where T and C are the total rainfalls in target and control areas in the type of periods indicated was 1.26. If the experiment had terminated at that point, the one sided significance level, by regression analysis using a cube root transformation, would have been 0.02. A similar plot for the first year's operation in New England is given as figure 4, this time for north seeded and south seeded periods.

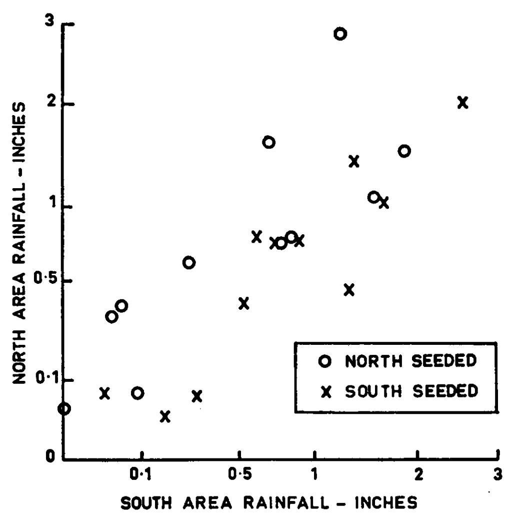

FIGURE 4

New England experiment.
First year's results.
Period rainfalls in north and south areas
in north seeded and south seeded periods.

The Root Double Ratio $[N/S \text{ (north seeded)}/N/S \text{ (south seeded)}]^{1/2}$ was 1.32 and if the experiment had stopped at that point, the significance level would have been 0.01 (regression; square root).

At this stage results appeared to be extremely heartening. The method stimulated rain from individual clouds and appeared to cause a substantial increase in rainfall in selected climates but not in others.

3.3. *Area experiments—final results.* The impressive results from the early stages of the experiments were not maintained. Results deteriorated and the final results for the complete experiments are shown in table I, in which the "observed result" is the Double Ratio, or Root Double Ratio, as defined above.

TABLE I

AREA EXPERIMENTS—FINAL RESULTS

Experiment	Duration Years	Observed Results	Significance Level (one sided)
Snowy Mountains	5	1.19	0.05
South Australia	3	0.95	0.7
New England	6	1.04	0.1
Warragamba	4	0.97	0.6

Two experiments gave positive results and two negative; the significance levels of both the Snowy Mountains and New England experiments had retreated to a marginal level. In general the overall results looked unconvincing and did not justify any definite statement as to whether, in these experiments, seeding had increased the rain or not. Rather, it appeared that such questions should be postponed until the anomalies revealed, such as the good beginning and poor ending, had been investigated. *Post hoc* analyses of the results of the same experiments cannot of course alter the conclusions, but are undertaken nevertheless in the next section; if they seem to show that seeding had results other than those expected, they may suggest hypotheses which may be tested in future experiments, and may also suggest improvements in the experimental design.

4. Limitations of area experiments

4.1. *Assumption that seeding effects are limited in time.* In the design of the area experiments, it was assumed that the effects of seeding during one "period" (of 14 days or 1 day) would not overlap appreciably into the next period. Observations during the experiments suggest that this assumption was unjustified; seeding appears to have had effects that lasted for a long time after the seeding stopped.

The observed result (Double Ratio or Root Double Ratio, section 3.2) may be calculated for each year of each experiment. Results are shown in figure 5 with least squares lines fitted. In every case the results deteriorated with time, all at about the same rate. Figure 6 shows the same data as the first year's results,

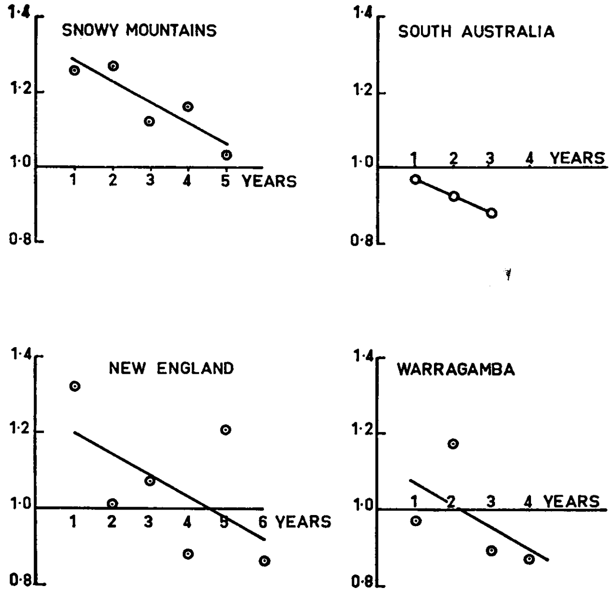

FIGURE 5

Variation of observed result with time in each experiment.
(Ordinate is Double Ratio for Snowy Mountains,
Root Double Ratio for others.)

second year's results and subsequent results for all four Australian experiments grouped together, suggesting that seeding had positive effects in the first two years but produced no detectable changes thereafter. A decrease seems to have occurred either in the rainfall increases caused by seeding or in the ability of the experiments to detect them.

TABLE II

AUSTRALIAN AREA EXPERIMENTS
VARIATION OF OBSERVED RESULT WITH TIME

Experiment	Year: First	Second	Third	Fourth	Fifth	Sixth
Snowy Mountains	1.26	1.27	1.12	1.16	1.03	
South Australia	0.97	0.92	0.88			
New England	1.32	1.01	1.07	0.88	1.21	0.86
Warragamba	0.97	1.17	0.89	0.87		

The reason for this deterioration in observed results is not definitely established. It is of course possible that a form of statistical bias may have contributed to it, but it seems most unlikely that this could be the sole cause. The obser-

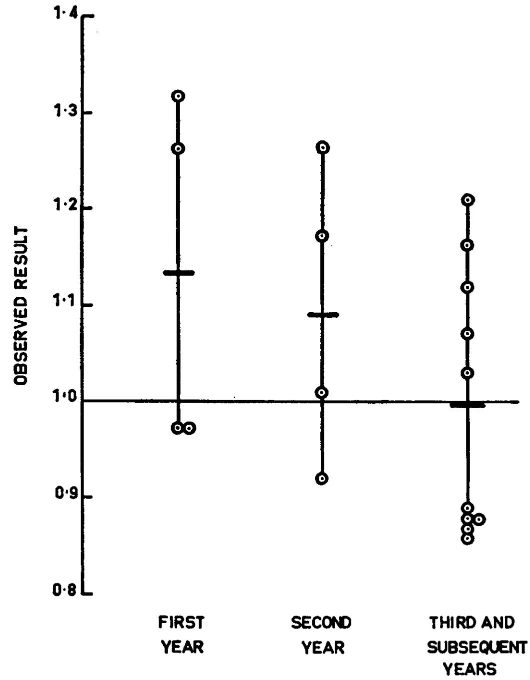

FIGURE 6

Observed result
in first, second, and subsequent years.
Four Australian experiments combined.
Short horizontal lines represent mean result for year.

vations are consistent with the deterioration being due, at least in part, to persistent effects of seeding.

Grant [4] has observed ice nuclei concentrations in a seeded area which increased when seeding commenced and remained high for several months after the seeding stopped. If this effect occurred during the Australian cloud seeding experiments (or any other effect whereby seeding of short duration caused rainfall changes of long duration) the ability of the experiments to detect changes caused by seeding would be reduced, because effects caused in one period would spread into the next. These consequences of persistent effects of seeding have been described by Bowen [3]. In the Australian experiments, the observations suggest that the half period of this process was of the order of many months.

Persistent effects of seeding would be expected to be more detrimental to the results of experiments with short "periods" than with longer ones. The yearly values of the observed results of the Australian experiments are shown in figure 7, separated according to period length (Warragamba, one day; other experiments about 14 days). The evidence is far from conclusive (and may be confused

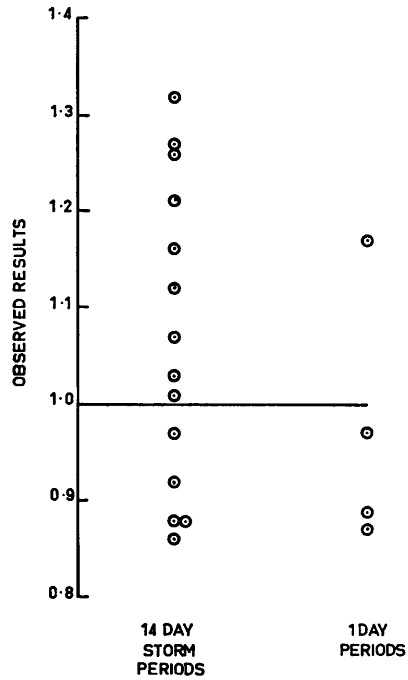

FIGURE 7

Yearly value of observed result.
Variation with period length.
Four Australian experiments.

by other factors such as climate) but the better results were associated with the longer periods.

4.2. *Assumption that results of seeding are constant.* In the experimental design it was assumed that the results of seeding would be more or less constant from one period to the next. This assumption was implied in all sorts of calculations, such as the time it was likely to take to achieve a given significance level. However, there is evidence that the results of seeding on rainfall are very variable and may sometimes be negative.

Correlations between the rainfalls in the areas behaved in an unexpected manner. In the New England experiment, the correlation between monthly rainfalls was lower during the experiment ($r = 0.72$) than in previous periods of the same length using the same gages ($r = 0.74, 0.73, 0.81, 0.77, 0.79, 0.81$), suggesting that the seeding had reduced the correlation. Also, the correlation between the period rainfalls during the experiment differed significantly according to which area was seeded ($r = 0.74$, north seeded and 0.87, south seeded); a similar result was observed in the South Australian experiment, in both cases without significant displacement of the mean value. These and other similar

observations suggest that the effect of seeding was sometimes to increase rain and sometimes to reduce it.

This would have two consequences in cloud seeding experiments of this type. First, the mean change in rainfall due to seeding would be the algebraic sum of all the changes and might be small, or zero, even if substantial changes were in fact caused. Secondly, the change would be more difficult to detect because the rainfall correlations would be reduced.

It became obvious that the circumstances in which a reduction in rainfall might be caused by seeding should be investigated, one possibility being that the effects of seeding are related to the temperature of the cloud tops.

In the experiments on single cumulus clouds (section 2), when the cloud top temperature was $-10°$ C or colder, rain from seeded clouds greatly exceeded that from unseeded clouds (figure 1). However, when the cloud tops were warmer than $-10°$ C the seeded clouds yielded less rain than the unseeded clouds (figure 8). The number of cases is too small to enable any conclusions to be

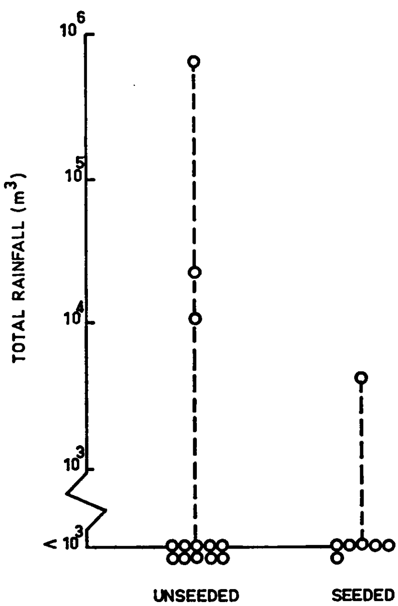

FIGURE 8

Total rainfall from isolated cumulus clouds.
Tops warmer than $-10°$ C.
Seeded and unseeded.

drawn as to the effects of silver iodide on the warm clouds but it is clear that they are different from the effects on colder clouds. In the area experiments, the observed results from cumuliform or mixed clouds varied with the cloud top temperature as shown in table III [1]. They are calculated for seeded days only

TABLE III

VARIATION OF OBSERVED RESULT WITH CLOUD TOP TEMPERATURE
SEEDED DAYS—CUMULIFORM CLOUD

Cloud Top Temperature	$-10°$ C and Colder	Warmer than $-10°$ C
New England	1.42	0.96
Warragamba	1.10	0.75
South Australia	1.24	0.93

and the results are based on observations of clouds in the target areas only. (This analysis cannot be performed for the Snowy Mountains experiments as suitable data are not available.) These results must thus be treated with due reserve as they are statistically biased; however, they are consistent with the results of the single cloud investigation in suggesting rainfall increases due to seeding cold clouds and decreases due to seeding warmer clouds.

4.3. *Experimental sensitivity limited by variations in rainfall gradients.* In the design stages of the experiments, historical correlations between the rainfalls in proposed areas were examined. In general, very few gages were available and the correlations were indifferent. Many more gages were installed for the experiment on the assumption that the correlations would be markedly improved, as would be expected if the correlations had been limited largely by sampling errors due to small scale spatial variations in rainfall. The improvement in correlation actually achieved by this means was less than had been hoped; as an example, during the New England experiment the correlation coefficient between the monthly readings of five raingages in each area was 0.72, while using the full network of 145 and 106 gages in the two areas the value rose to 0.78. More gages gave a better measure of the area rainfalls but they were still indifferently correlated due to variations in the rainfall gradients.

The Australian experiments are in general located on mountain ranges running north-south with prevailing westerly winds. The main gradients in these circumstances are east-west and the experimental areas were accordingly aligned north-south. However, weather systems passing north or south of the pairs of areas caused temporary gradients between them of appreciable magnitude and either sense. These often had a duration comparable with the cloud seeding "periods" used, but also varied with season, in either case limiting the rainfall correlations.

A special case of rainfall gradient (either in space or time) is sometimes encountered, in the form of local rainfalls of very high intensity. These can confuse the statistical evaluation of results.

5. Design requirements for future experiments

The limitations of past experiments discussed in the previous section must be overcome if definite answers are to be provided to questions, such as whether

seeding can alter rainfall, whether the alterations are always positive or sometimes negative and in what circumstances, and whether and by what means the effects persist after the seeding stops. Specific suggestions follow.

5.1. *Persistent effects of seeding.* Future experiments should be designed in such a way that if persistent effects of seeding occur they may be detected and investigated.

(i) *Operation in alternate years.* It is assumed that seeding will be based on a random schedule, which decides either that clouds over a target area shall or shall not be seeded, or which of two target areas should be seeded, in a given period. This seeding schedule should itself be turned on and off at intervals which are fairly long compared with the expected duration of the persistent effects; in the first instance a year on, year off operation is suggested.

(ii) *Unseeded control areas.* A control area or areas should be provided which are never seeded. Then persistent effects of seeding should cause the ratio of precipitation in the target areas to that in the control areas to change progressively during the "on" years, returning to normal during the "off" years. In this case the increase detected by analysis of the seeded and unseeded period rainfalls might represent only part of the change due to seeding. An example of the sort of thing which might happen [3] is given as figure 9. In this type of investigation

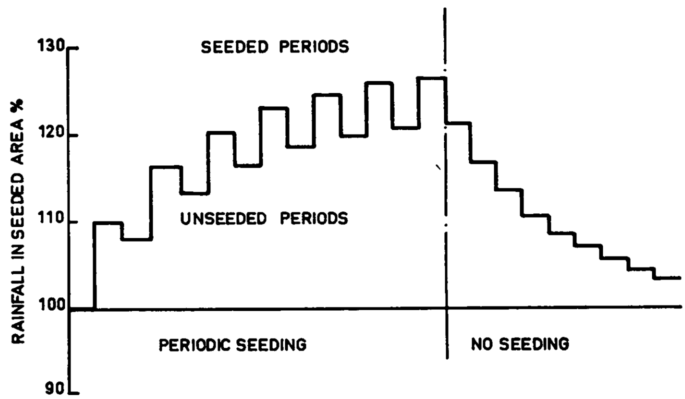

FIGURE 9

Growth and decay of the results
of a cloud seeding experiment in which
there is an increase of precipitation of 10 per cent
per seeded period and a persistence of 0.8 (after Bowen)

it is necessary to allow for any seasonal variations in the T/C ratio, the effects of seeding being revealed by the differences in rainfall figures in "on" and in "off" years.

(iii) *Period analysis.* It is also necessary to analyze the rainfall figures for the randomized periods during the "on" years in such a way as to minimize any loss

of sensitivity which might be caused by persistent effects of seeding. For this reason it is desirable to use long periods (*e.g.* two weeks rather than one day) and to use methods of analysis which are affected as little as possible by progressive changes in the ratio of rainfall (whether seeded or unseeded) in the target and control areas.

5.2. *Variability of results.* If the results of seeding are sometimes positive and sometimes negative, as suggested in section 4.2, the future cloud seeding experiments should be designed in such a way as to reveal as much as possible about these effects. Attempts to do this might be confused if seeding has persistent results, but the attempt should nevertheless be made; suggestions follow.

(i) *Variance changes.* It must be possible to detect rainfall changes in either direction, not only changes in the mean value. A year on, year off operation would be helpful in this respect as the variance in the rainfall and rainfall relationships between target and control areas can be compared in the two sorts of year.

(ii) *Stratification of results.* It must be possible to isolate the circumstances in which rainfall reductions occur. This may be undertaken in separate experiments of a different sort, but in the area experiments provision should be made for stratification of results without confusion from statistical bias.

(iii) *Choice of clouds to be seeded.* A choice must be made in the seeding technique to be employed. If the maximum increase in rainfall is desired, then no seeding should take place in circumstances thought likely to lead to reductions in rainfall. Alternatively seeding could take place in these circumstances, the results being separated in the analysis.

5.3. *Allowance for rainfall gradients.* In the experiments described in section 3.1, rainfall in the target area during a "period" was compared with an expected value based on rainfall in a control area during the same time. In this process it is desirable to allow for any variations in the rainfall gradient between the two areas. If two control areas are provided, one on each side of the target area or areas, they can be used to measure the rainfall gradient across the region and allowance can be made in the results.

6. Future program

The future cloud seeding research program of the Radiophysics Division of the CSIRO follows two paths. First, investigations are being conducted into the physical processes of glaciation, nucleation, and so forth, on which cloud seeding depends. Secondly, a new series of experiments is being started in which clouds are seeded over areas.

The first objective is to determine the amount by which silver iodide, released from an aircraft, can increase the rain over specified areas of country. In this respect they resemble the first series of experiments, but the suggestions of section 5 have been incorporated, which should improve the sensitivity and increase the chance of success. The second objective is to detect persistent

effects of seeding if they occur, and to measure their characteristics such as amplitude and time constant. The third objective is to gather information as to the circumstances in which rainfall increases, or decreases, can be achieved.

The first of these new experiments is in Tasmania; the areas are illustrated in figure 10. The target area is seeded or not seeded on a random basis. The rainfall

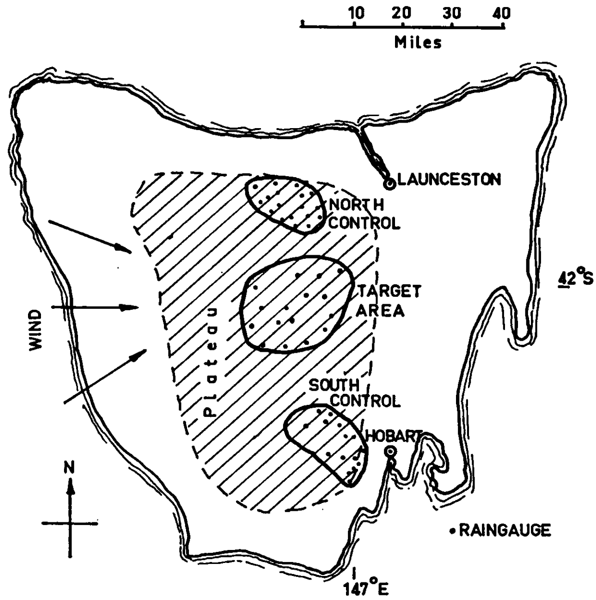

FIGURE 10

New experiment in Tasmania.
Layout of areas.

in the target area is compared with the mean of those in two control areas, one on each side of the target; the correlation coefficient in historical records between monthly rainfalls being 0.94, compared with 0.85 between the target area and either control alone. Seeding takes place in alternate years but rainfall measurements are made in all years.

Randomization is by periods of 10 to 18 days, changing on days of forecast fine weather. Provision is made for rejecting days of exceptional rainfall, using an objective criterion based on the rainfall in the control areas.

Evidence of persistent effects of seeding will be sought in the way in which the target to control area rainfall ratio changes during seeded and unseeded years (section 5.1).

During the seeded years, observations will be made of meteorological conditions in both seeded and unseeded periods, providing a basis for unbiased stratification of data which should lead to conclusions as to the conditions in

which rainfall changes can be caused. Cumuliform clouds with tops warmer than $-10°$ C will not be seeded.

7. Conclusion

Experiments in Australia have made it appear that cloud seeding with silver iodide has considerable potential for modifying the rainfall. However, the effects are not simple and early experiments appear to have been confused by effects of seeding which persisted after the seeding stopped, and were sometimes positive and sometimes negative. Experiments of improved design, incorporating the requirements described in section 5, will be necessary to reveal the full possibilities and limitations of the technique.

If the persistent but variable results are confirmed, two problems will arise. First, how should the seeding technique be employed in order to provide the greatest practical benefit? Secondly, from results possibly resembling the idealized concept of figure 9, but complicated by various physical factors which presumably will be involved, what statistical techniques should be employed to determine the real increase due to seeding and its significance level?

I acknowledge with appreciation the contributions to the work described in this paper of the Chief of the Radiophysics Division, Dr. E. G. Bowen, of my colleagues E. E. Adderley and F. D. Bethwaite, of the Commonwealth Bureau of Meteorology, the Snowy Mountains Hydroelectric Authority and the New South Wales and South Australian State Departments of Agriculture, and to all those who contributed to the many phases of the experiments, from organization through flying and rainfall measurements to analysis.

REFERENCES

[1] F. D. Bethwaite and E. J. Smith, "The effects of cloud-top temperature on the results of cloud-seeding with silver iodide," in preparation.

[2] F. D. Bethwaite, E. J. Smith, and J. A. Warburton, "Effects of seeding isolated cumulus clouds with silver iodide," submitted to *J. Appl. Meteor.*, 1966.

[3] E. G. Bowen, "The effect of persistence in cloud-seeding experiments," *J. Appl. Meteor.*, Vol. 5 (1966), pp. 156–159.

[4] L. O. Grant, "Indications of residual effects from silver iodide released into the atmosphere," *Proceedings 31st Annual Meeting, Western Snow Conference*, Fort Collins Colorado State University, 1963, pp. 109–115.

[5] E. J. Smith, "Experiments in seeding cumuliform cloud layers with dry ice," *Austral. J. Scient. Res. A*, Vol. 2 (1949), pp. 78–91.

[6] E. J. Smith, E. E. Adderley, and F. D. Bethwaite, "A cloud-seeding experiment in South Australia," *J. Appl. Meteor.*, Vol. 2 (1963), pp. 565–568.

[7] ———, "A cloud-seeding experiment in New England, Australia," *J. Appl. Meteor.*, Vol. 4 (1965), pp. 433–441.

[8] ———, "A cloud-seeding experiment in the Warragamba Catchment, Australia," in preparation.

[9] E. J. SMITH, E. E. ADDERLEY, and D. T. WALSH, "Cloud-seeding experiment in the Snowy Mountains, Australia," *J. Appl. Meteor.*, Vol. 2 (1963), pp. 324–332.

[10] E. J. SMITH and K. J. HEFFERNAN, "The decay of the ice-nucleating properties of silver iodide released from a mountain top," *Quart. J. Roy. Meteor. Soc.*, Vol. 82 (1956), pp. 301–309.

[11] E. J. SMITH, K. J. HEFFERNAN, and B. K. SEELEY, "The decay of ice-nucleating properties of silver iodide in the atmosphere," *J. Meteor.*, Vol. 12 (1955), pp. 379–385.

[12] E. J. SMITH, K. J. HEFFERNAN, and W. J. THOMPSON, "The decay of the ice-nucleating properties of silver iodide released from an aircraft," *Quart. J. Roy. Meteor. Soc.*, Vol. 84 (1958), pp. 162–165.

[13] P. SQUIRES and E. J. SMITH, "The artificial stimulation of precipitation by means of dry ice," *Austral. J. Scient. Res. A*, Vol. 2 (1949), pp. 232–245.

[14] J. WARNER and S. TWOMEY, "The use of silver iodide for seeding individual clouds," *Tellus*, Vol. 8 (1956), pp. 453–459.